ADVANTAGES AND DRAWBACKS OF NEAR-FIELD CHARACTERIZATION OF LARGE APERTURE SYNTHESIS RADIOMETERS

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ABSTRACT
Accurate characterization of an aperture synthesis radiometer requires making measurement of its performances inside an anechoic chamber. However, due to size limitations, the sources used in the process have to be located at distances too short to be able to apply the far-field condition of the instrument. Although the fundamental equation of aperture synthesis radiometry derived for far-field fails in this case, it is still possible to measure most of the critical parameters such as spatial resolution, sensitivity or impulse response using point sources inside an anechoic chamber. Nevertheless, it is not possible to retrieve images of complex shapes, so near field characterization must be complemented with open air measurements of complex images. Near-field techniques have been used to characterize a reduced model of MIRAS and are being considered also for further characterizations of the whole instrument during the phases C/D of the SMOS mission.

1. INTRODUCTION
Two-dimensional interferometric radiometry is a promising technique for Earth observation and it is the concept selected for SMOS (Soil Moisture and Ocean Salinity), an Earth Explorer mission of the European Space Agency (ESA) aimed at providing global soil moisture and sea salinity maps [1]. Its main payload is MIRAS, an L-band interferometric radiometer with a large number of small elements (antennas + receivers) distributed along a large Y-shaped structure, so as to achieve a spatial resolution similar to a real aperture radiometer having the same size of the whole instrument [2]. Before launching the radiometer into space it has to be thoroughly characterized on ground in order first to check its basic operation, and second to validate the calibration and inversion algorithms. This is specially important due to the novelty of the technique, which has not been used before in microwave Earth remote sensing. This on-ground characterization can be performed in open air, but it is more convenient to do it -at least as a first step- in a controlled environment, e.g. an anechoic chamber.

The basic measurement of an interferometric radiometer is the so-called “visibility function,” obtained from the measured complex cross-correlation of the signals collected by pairs of elements. For on-ground characterization, due to size limitations of the chamber, the sources are too close to the instrument to consider valid the paraxial approximation in the fundamental equation that relates visibility function and brightness temperature. Then, even for ideal receivers, the relationship between the brightness temperature and the visibility is no longer a Fourier Transform and appropriate correction techniques have to be implemented to convert the measured data to their equivalent values in “far field.” Note that the “far” and “near” adjectives are referred to the whole instrument, so this nomenclature does not mean that each individual antenna is operating in its near-field region.

In this paper details of the basic equations of the near- to far-field transformation are given. Also some results of the application of this technique to characterize a reduced model of MIRAS inside an anechoic chamber are described [3]. Finally, its main advantages and limitations are discussed.

2. NEAR AND FAR FIELD VISIBILITY
For two separated antennas pointing to a thermal source, the frequency domain visibility $V_{ij}$ is conveniently defined in terms of the cross-power spectral density of the waves coming from the source and collected by the antennas $b_i$, $b_j$, such that $b_i b_j^* = K V_{ij}$ where $K$ is the Boltzmann constant. For a spatially uncorrelated source, $V_{ij}$ can be computed by adding the elementary contributions of all the infinitesimal source elements. The general equation when the separation between antennas is much smaller than the distance to the source is [4]

$$V_{ij} = \frac{\sqrt{D_i D_j}}{4\pi} \int_{\Omega} T_B(\theta, \phi) F_{n_i}(\theta, \phi) F_{n_j}^*(\theta, \phi) e^{i \Delta \varphi} d\Omega$$

where $d\Omega$ is the solid angle subtended by the elementary source at angular coordinates $(\theta, \phi)$, $F_{n_i}(\theta, \phi)$ stands for normalized voltage antenna pattern and $T_B(\theta, \phi)$ is the brightness temperature of the source in the direction $(\theta, \phi)$ at the polarization base of the antennas. For simplicity these ones are assumed as having identical polarization vector. The symbol $D$ is used for antenna maximum directivity.

The exponential term accounts for the phase difference of the waves coming from a source element to each antenna, so

$$\Delta \varphi \approx -k (\xi \Delta x + \eta \Delta y)$$

where $\xi = \sin \theta \cos \phi$ and $\eta = \sin \theta \sin \phi$ are the direction cosines and the antennas are assumed in the $X - Y$ plane. This approximation leads to the familiar Fourier-like integral relating the visibility to the modified brightness temperature, currently used in interferometric radiometry and radioastronomy.

However, if the distance from the source to the antennas is reduced, this approximation is no longer valid and conventional inversion techniques can not be applied. Moreover, in
this case the angular coordinates of a given source element $(\theta, \phi)$ are different for each antenna, making (1) completely wrong. In other words, in near-field condition no imaging is possible.

Nevertheless, two special cases can be solved. First, if the source consists of a microwave absorber completely surrounding the antennas (that is, an anechoic chamber) kept at constant temperature equal to that of the receivers or, in other words, if thermodynamic equilibrium is assumed, then, by application of the Bosma theorem [5], the measured cross-correlation of the total output signals must vanish [4]. And this does not depend on the chamber size, so the near-field condition does not affect the result.

The second situation is when the source is of very small extent, or, in the limit, it is a point source. Then the integration region is limited to a small solid angle in the direction of the source and the equation is no longer an integral. This is analyzed more in detail in the following subsection.

Due to the linearity of the equation, a large aperture synthesis radiometer can be characterized inside an anechoic chamber provided only one point source is present and that the physical temperature of all elements are kept constant. In this case, only the contribution of the point source must be analyzed and used in the characterization.

### 2.1 Point sources

If the solid angle subtended by the source looking from any antenna is sufficiently small so that the antenna patterns can be considered constant inside it, the frequency domain visibility can be written as

$$V_{ij} = T_B F_{n_i}^\prime (\theta_i, \phi_i) F_{n_j}^\prime (\theta_j, \phi_j) e^{-jk(r_i-r_j)} \frac{A}{r_ir_j}$$  \(2\)

where $A$ is the area of the source, $T_B$ its brightness temperature, $r_i$ and $r_j$ the distances from both antennas to the source and the definition $F_{n_i}^\prime (\theta, \phi) = \sqrt{\frac{\pi}{4\pi}} F_n (\theta, \phi)$ is used to simplify the notation. Note that the direction of the vector from each antenna to the source is different.

The equivalent far-field visibility is defined as the one that results of making the paraxial approximation:

$$V_{ij}^F = T_B F_{n_i}^\prime (\theta_0, \phi_0) F_{n_j}^\prime (\theta_0, \phi_0) e^{-j2\pi(u_x+u_y)} \frac{A}{r^2}$$  \(3\)

where $\theta_0$ and $\phi_0$ are the directions of the vector going from a conveniently defined center of coordinates to the source, $r$ is the distance from this center to the source, $u=(x_j-x_i)/\lambda$ and $v=(y_j-y_i)/\lambda$ where $\lambda$ is the wavelength. Note that this equation can be obtained directly from (1) only by assuming a source of limited and small extent and using the paraxial approximation.

Now, if the source location is known, it is possible to compute the equivalent far-field visibility from the actually measured visibility by multiplying by a constant derived easily from (2) and (3). Once $V_{ij}^F$ is computed, a Fourier algorithm can be used to retrieve the brightness temperature image of the small source.

### 3. Experiments in Near Field Condition

Near field characterization is useful to measure several important characteristics of the instrument, such as the spatial resolution, the impulse response or the sensitivity. Also, calibration techniques can be assessed since calibration is performed by processing the raw data to compute the visibility and it is independent of the inversion process. Fig. 1 shows a photograph of a setup used to characterize a reduced model of MIRAS in near field. The walls of the anechoic chamber are clearly seen, as well as a crane to support one or two small sources, mainly consisting of antennas driven by noise generators.

#### 3.1 Spatial resolution and impulse response

The spatial resolution was measured by imaging two separate sources consisting of two antennas acting as emitters. One source was placed at the instrument boresight and the other separated the angular resolution ($3.9^\circ$ for Blackmann window). After inversion, the two point sources should be identified. As explained in the previous section, it is impossible to retrieve the temperature distribution from both antennas radiating simultaneously because of the near-field to far-field transformation. In order to process data it is necessary to put one antenna in the anechoic chamber, do the measurements, then make the transformation and repeat it for the other antenna. The superposition of the two far-field visibilities is equivalent to the measurement of the visibility from the two antennas in far field directly.

The result is given in Fig. 2 where two images are shown. The first one corresponds to the source off-boresight (at $\xi = 0$, $\eta = -0.068$) while the other one to the superposition of both sources. As can be seen, the location of the single source is accurately retrieved since the maximum is at the expected point separated from boresight. Moreover, two peaks are seen in the second image, showing that effectively the addition of the far-field visibilities allows simulating a measurement with two sources simultaneously.

Once the visibilities of the two measurements are added, the inversion algorithm allows to obtain the final image as if the two sources were in the far field. Blackmann window...
was applied to the visibilities prior to invert them and this was performed using hexagonal Fast Fourier transform with the algorithm described in [6]. The results show that the instrument can distinguish two point sources located a single pixel apart.

### 3.2 Sensitivity circles

A convenient way to characterize a baseline is by means of the so-called sensitivity circles [7]. They are plots in the complex plane of the normalized cross-correlation measured between two receivers while sweeping the phase of the local oscillator of one of them from 0 to 360°. If the receivers and correlator operate correctly, the measurements should show a circular shape describing a single turn.

Using the raw data, two sets of circles can be drawn, corresponding to different output signals used to compute the complex correlation: the “nominal value,” defined as \( \mu^N = \mu_{iq} + j\mu_{iq} \), and the “redundant value,” \( \mu^R = \mu_{qq} + j\mu_{qq} \). The superscripts \( i \) and \( q \) refer to the in-phase and quadrature outputs of the receivers. Theoretically, both complex correlations should give the same result but if receiver noise temperature of each of the two IF branches is different they may differ. In particular, if receiver number “0” is taken as reference, the nominal and redundant normalized complex correlations relating receiver “m” are

\[
\begin{align*}
\mu^N_{0m} &= R \left( \frac{r_{m0}^0(0)T_C}{T_{sys}^0 T_{sys}^m} \right) + j \Im \left( \frac{r_{m0}^0(0)T_C}{T_{sys}^0 T_{sys}^m} \right) \\
\mu^R_{0m} &= R \left( \frac{r_{m0}^q(0)T_C}{T_{sys}^0 T_{sys}^m} \right) + j \Im \left( \frac{r_{m0}^q(0)T_C}{T_{sys}^0 T_{sys}^m} \right)
\end{align*}
\]

where \( T_C \) is the equivalent correlated temperature at receivers input and \( r_{m0}^0(0) \) is the fringe washing function at zero lag defined between corresponding receivers’ outputs. Receiver phase and quadrature errors are included in the fringe-washing terms. Adding a phase shift in the local oscillator of receiver number “0” is equivalent to adding a constant phase to the fringe washing function so effectively changing the phase of the correlation. If thermal noise is present, an error vector is added to the complex correlation, as it is shown in Fig. 3.

Simple inspection of the sensitivity circles is a potent tool for troubleshooting most of the baseline parameters, for example quadrature errors or I/Q amplitude unbalance. A more detailed list is given in tables 1 and 2.

Finally, note that the circles can be drawn both for raw data as well as for calibrated data. Since, after calibration all the circles should be perfect in shape, this is a very powerful means of checking if the instrument and the calibration algorithms work properly. It can be considered as a pattern test image.

The sensitivity circles are measured by applying correlated noise to the input of both receivers. To take into account all error sources, including the ones due to the antennas, the best approach is by using a probe antenna placed at the instrument boresight. This can be done in near field conditions, so this is a clear application of the technique presented in this paper.

An experiment was carried out using again the setup shown in Fig. 1. In this case only the boresight source was used and its power level was controlled by means of a variable attenuator. For increasing levels of attenuation, the circles must reduce their radius but they must preserve their shape. The value of input attenuation that produces a “highly distorted” plot sets the limit of detectable input signal (understanding signal as correlation, not absolute power), and hence the system’s sensitivity.

Some results are given in Fig. 4. It shows two distinct measurements differing from each other on the amount of attenuation inserted. The relative attenuation between both is 25 dB. The units used for both axes are “correlation units” defined as 1 c.u. = 10^{-8} units, so the circles in the left have a radius of roughly 0.7 units. It is seen that for low normalized correlations (about 10^{-3}) the errors in the receivers produce relatively high offset and general distortion of the circles, indicating that the receivers used (first prototypes) were

### Table 1. Features measured from circles at high level of correlation

<table>
<thead>
<tr>
<th>HIGH LEVEL OF CORRELATED NOISE</th>
<th>Cause</th>
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</thead>
<tbody>
<tr>
<td>Reduced circle radius in both nominal and redundant correlations</td>
<td>Higher receiver noise</td>
</tr>
<tr>
<td>Reduced circle radius only in nominal or redundant correlations</td>
<td>Higher noise in Q or I path, or different frequency response</td>
</tr>
<tr>
<td>Elliptic response</td>
<td>Residual quadrature error</td>
</tr>
</tbody>
</table>

### Table 2. Features measured from circles at low level of correlation

<table>
<thead>
<tr>
<th>LOW LEVEL OF CORRELATED NOISE</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erratic behavior</td>
<td>Higher offset or amplitude drift</td>
</tr>
<tr>
<td>Noisy circle</td>
<td>Interference signal</td>
</tr>
<tr>
<td>Redundant and nominal circles are misaligned</td>
<td>Different residual offset</td>
</tr>
</tbody>
</table>
4. CONCLUSION

Near-field characterization of large aperture synthesis radiometers is possible and useful. This is particularly important due to the need of measuring the whole instrument located inside an anechoic chamber to avoid RF interferences. Important parameters such as spatial resolution, impulse response or sensitivity, as well as calibration techniques can be characterized from near-field measurements using point sources. The main limitation of near-field measurements is that it is not possible to make an image of a complex source in a single snapshot. The only possibility is to image a collection of points, so near field characterization must be complemented with open air imaging validation. Sensitivity circles are proposed as powerful means of characterizing a baseline.

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5. REFERENCES


